2HDM @ Snowmass

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BNL Snowmass 4/4/13

2HDM are effective theories for extended EWSB

- Snowmass charge is to fully explore the origin of EWSB. Strongly motivates looking at direct extensions of the EWSB sector.

- Naturalness often implies extended Higgs sector.

- Two Higgs doublet models provide an effective theory description for many such EWSB extensions: Higgs sector of MSSM, various Twin Higgs models, various Composite Higgs models all described by 2HDM of various genres.

- *Much effort devoted to MSSM 2HDM signals, but this does not exhaust the signature space.*

We should systematically study 2HDM as effective theories for new physics.

- Look for five physical states: CP even scalars h,H; pseudoscalar A; charged Higgses H^+,H^-

A simplified parameter space

- General parameter space of 2HDM is vast. But there are well-motivated simplifying assumptions!

- Flavor limits suggest 2HDM should avoid new tree-level contributions to FCNC; satisfied by four discrete choices of couplings to fermions.

- Lack of large BSM CP violation suggests new sources of CP violation coupled to SM are small; motivates focusing on CP-conserving 2HDM potentials.

- Imposing these constraints leads to tractable parameter space for signals.

A simplified parameter space

If CP conservating, after EWSB there are 9 free parameters

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$

$$+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2) + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$

$$+ \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)\Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$

Useful basis consists of 4 physical masses, 2 angles, 3 couplings:

$$m_h, m_H, m_A, m_{H\pm} \qquad \alpha \quad \tan\beta \equiv \langle \Phi_2 \rangle / \langle \Phi_1 \rangle \qquad \lambda_5, \lambda_6, \lambda_7$$

Discrete symm. for flavor: $\lambda_{6,7} = 0$ MSSM: $\lambda_{5,6,7} = 0$

A simplified parameter space

|	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

Four discrete 2HDM types.
All couplings to SM states
fixed in terms of two angles!

y_{2HDM}/y_{SM}	2HDM I	2HDM II	2HDM III	2HDM IV
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
AVV	0	0	0	0
AQu	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

- Scalar self-couplings have additional parametric freedom.

- Gives a map between current fits to the Higgs couplings and the possible size of NP signals!

Interplay with h

Coupling measurements of the state at 126 GeV shape the space of likely signatures for heavier scalars
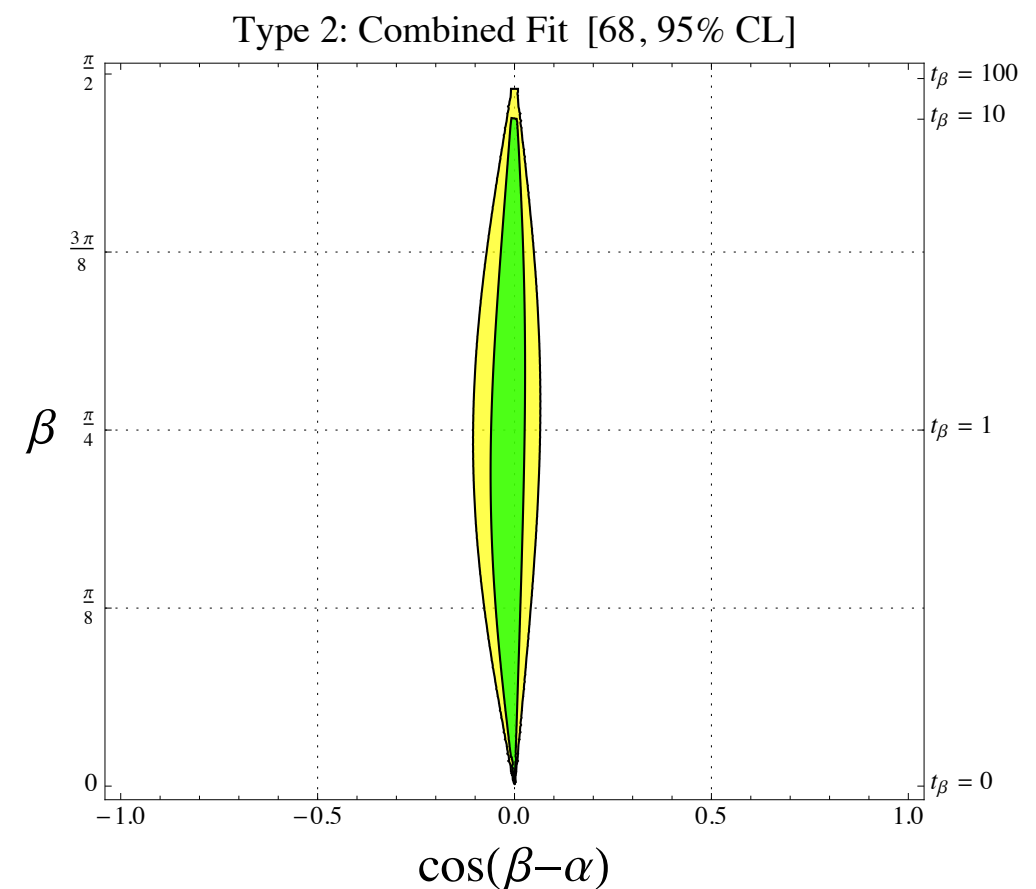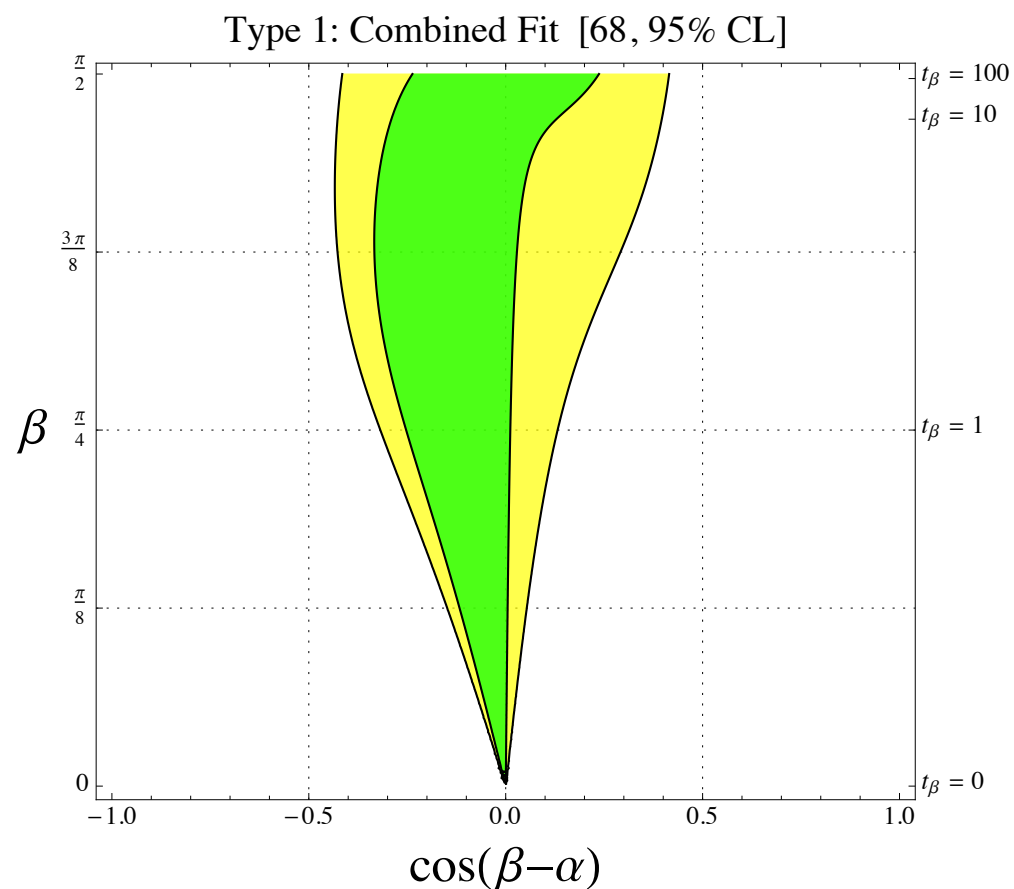
We are close to the decoupling limit!

(For more detail, see Marc Sher's talk this afternoon)

What to look for?

In decoupling limit, it's natural for

$$m_H \sim m_A \sim m_{H\pm} > m_h$$

In this case the kinematically available decays are:

- H decays to SM fermions, vectors, and also H→hh

- A decays to SM fermions, photons, and also A→Zh

- H⁺ decays to SM fermions and also H⁺→Wh

So which are the most important modes?

(In what follows I will mostly ignore the charged Higgs)

Life in the decoupling limit

$$y_{HVV}, y_{Hhh}, y_{AZh} \propto \cos(\beta - \alpha)$$

Vector couplings and multi-higgs couplings suppressed

Type 1:

$$y_{Hf\bar{f}} \propto \cos(\beta - \alpha) - \cot \beta$$

$$y_{Af\bar{f}} \propto \cot \beta$$

Fermion couplings generically suppressed but nonzero

Type 2:

$$y_{HQd}, y_{HLe} \propto \cos(\beta - \alpha) + \tan \beta$$

$$y_{AQd}, y_{ALe} \propto \tan \beta$$

Down-type quark and lepton couplings enhanced

Need a bit more to fix most promising channels...

Some 2HDM rules of thumb

$$\sigma(i) \cdot \mathrm{Br}(f) \propto y_i^2 \times \frac{y_f^2}{y_{\mathrm{dominant}}^2}$$

Production side: vector coupling suppressed, so need to rely on fermion couplings. *Gluon fusion is the best hope for H, A.*

Decay side: Total width set by dominant partial width. If decay mode and total width have same scaling, *doesn't matter if decay coupling is suppressed in decoupling limit.*

Rule of thumb I

Decays to vectors & Higgs often win.

$$\Gamma(H \rightarrow VV, hh) \propto m_H^3/v^2 \qquad \Gamma(H \rightarrow bb) \propto m_H m_b^2/v^2$$

So decays to higgs, vectors can win until
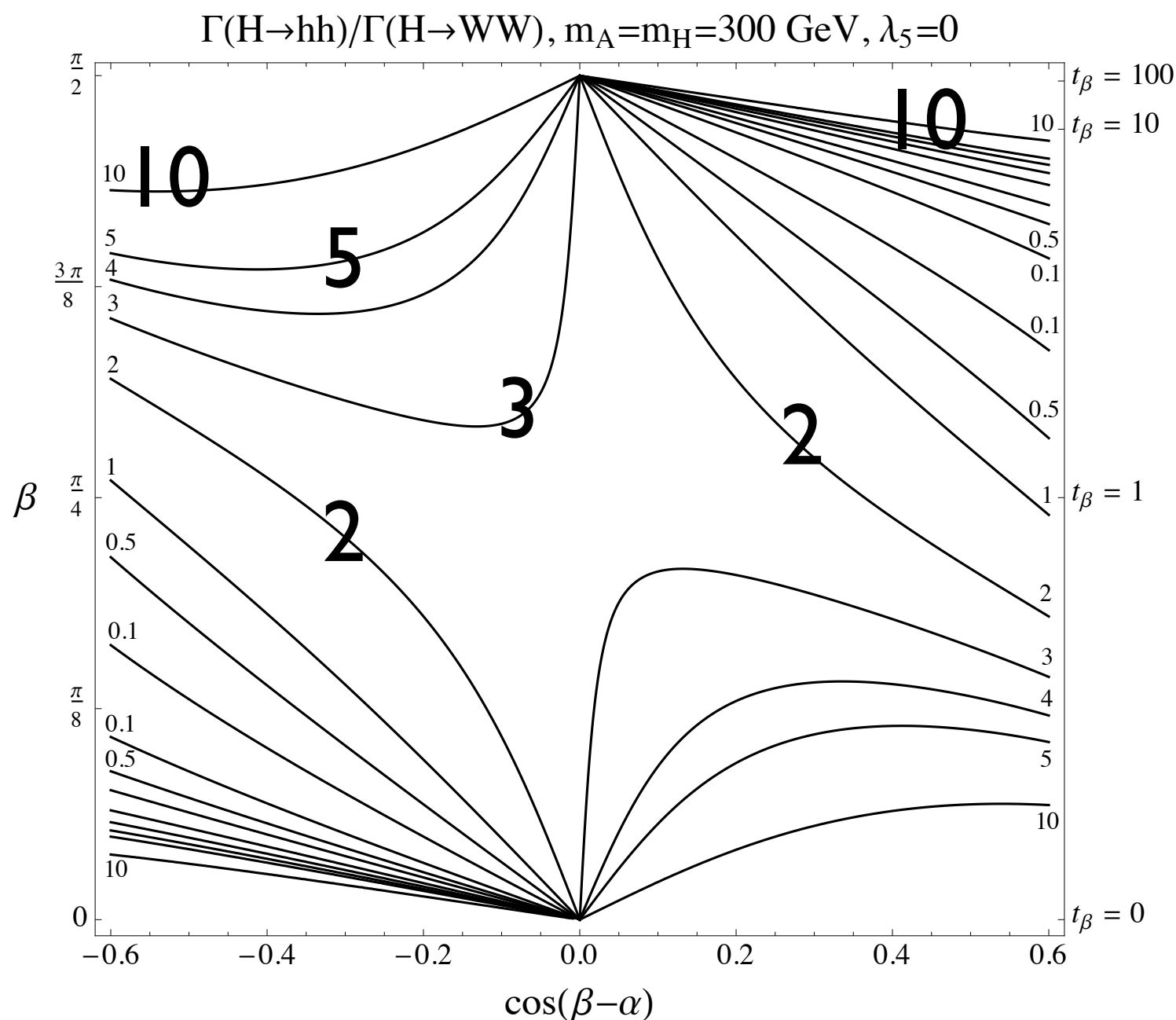
$$\cos(\beta - \alpha) \lesssim m_b/m_H$$

(though in Type 2, bottom coupling is tan beta-enhanced)

We are nowhere near being pinned this close to decoupling, so it is consistent for vectors and Higgs to dominate width.
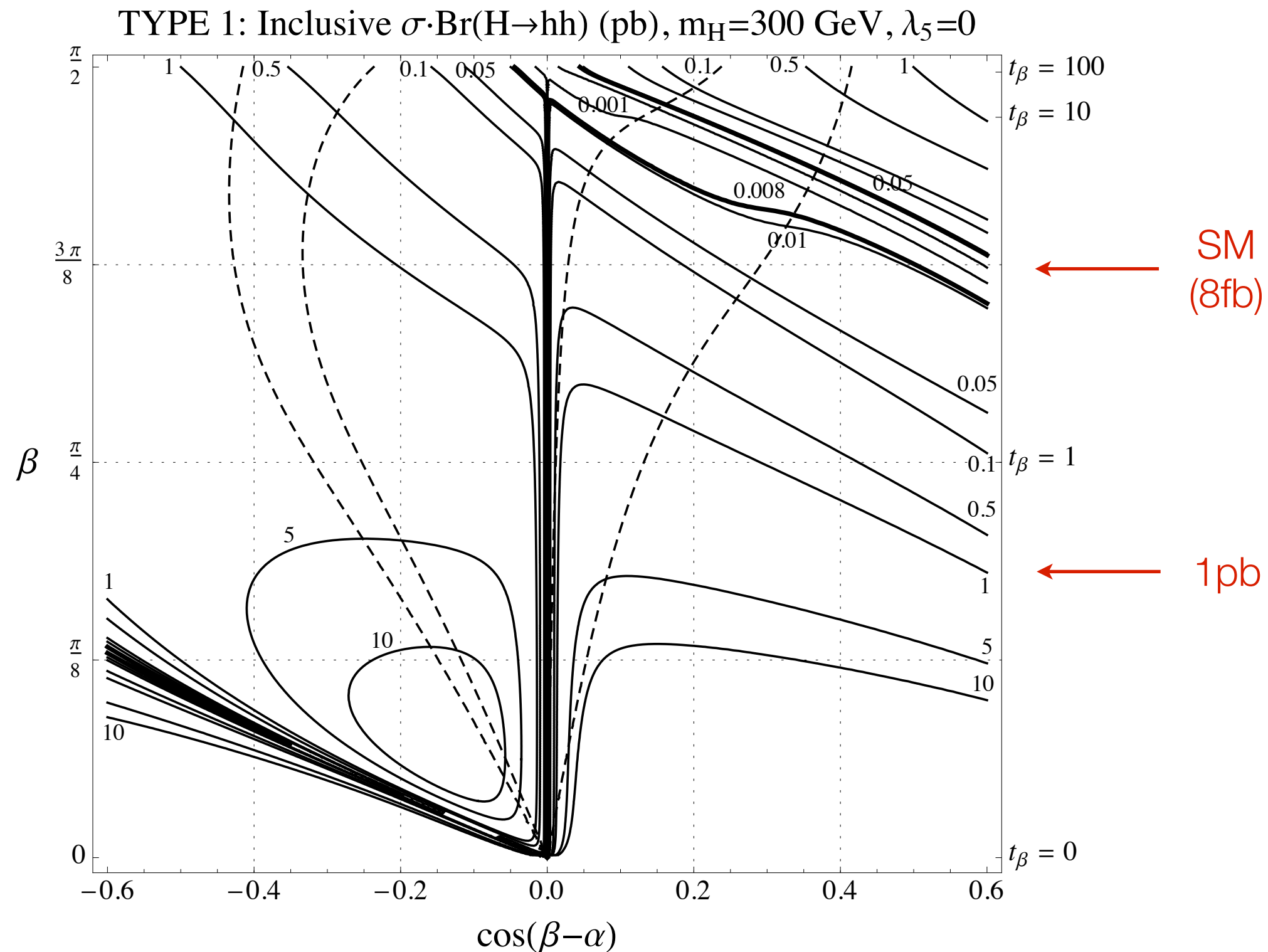
Same is true of A decaying to Zh

Rule of thumb 2

$$\Gamma(H \to hh) \quad \text{often beats} \quad \Gamma(H \to VV)$$

$\Gamma(H{\to}hh)/\Gamma(H{\to}WW)$, $m_A{=}m_H{=}300$ GeV, $\lambda_5{=}0$
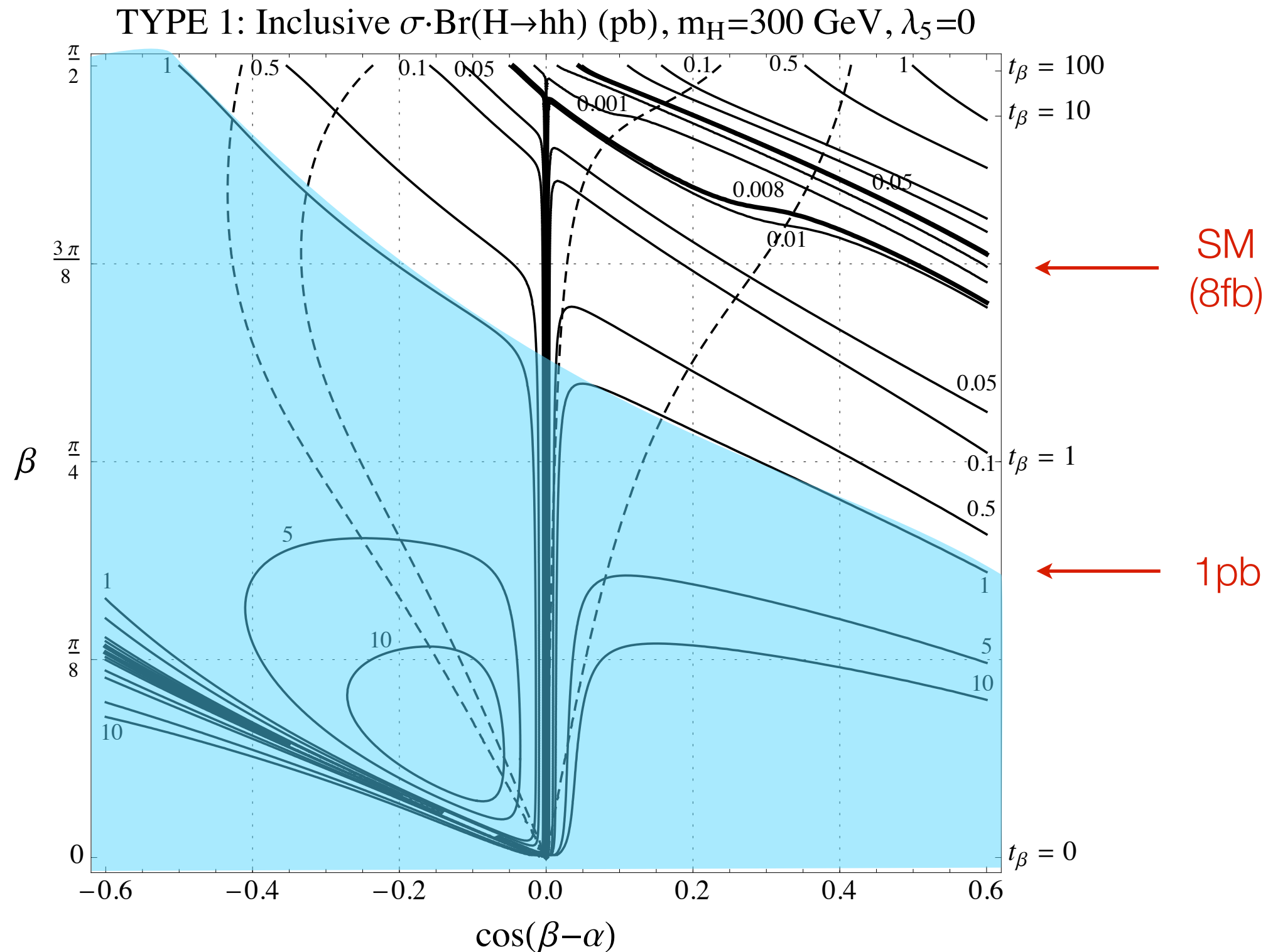
- Means BR to hh is often large!

- Also suppresses BR to vectors, weakens VV search at high mass.

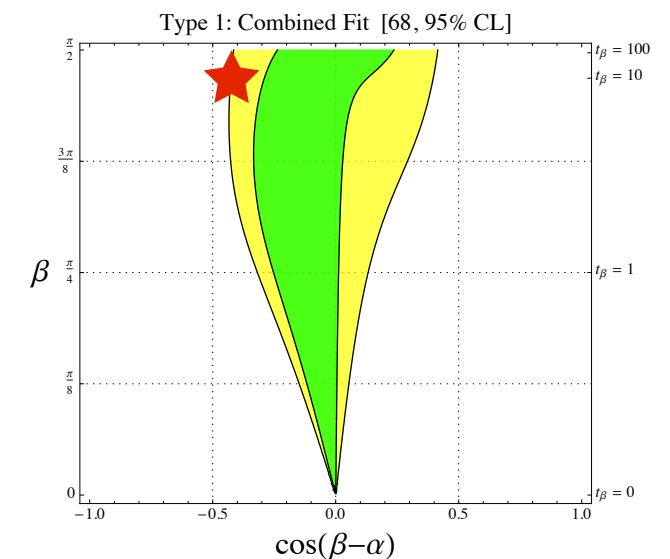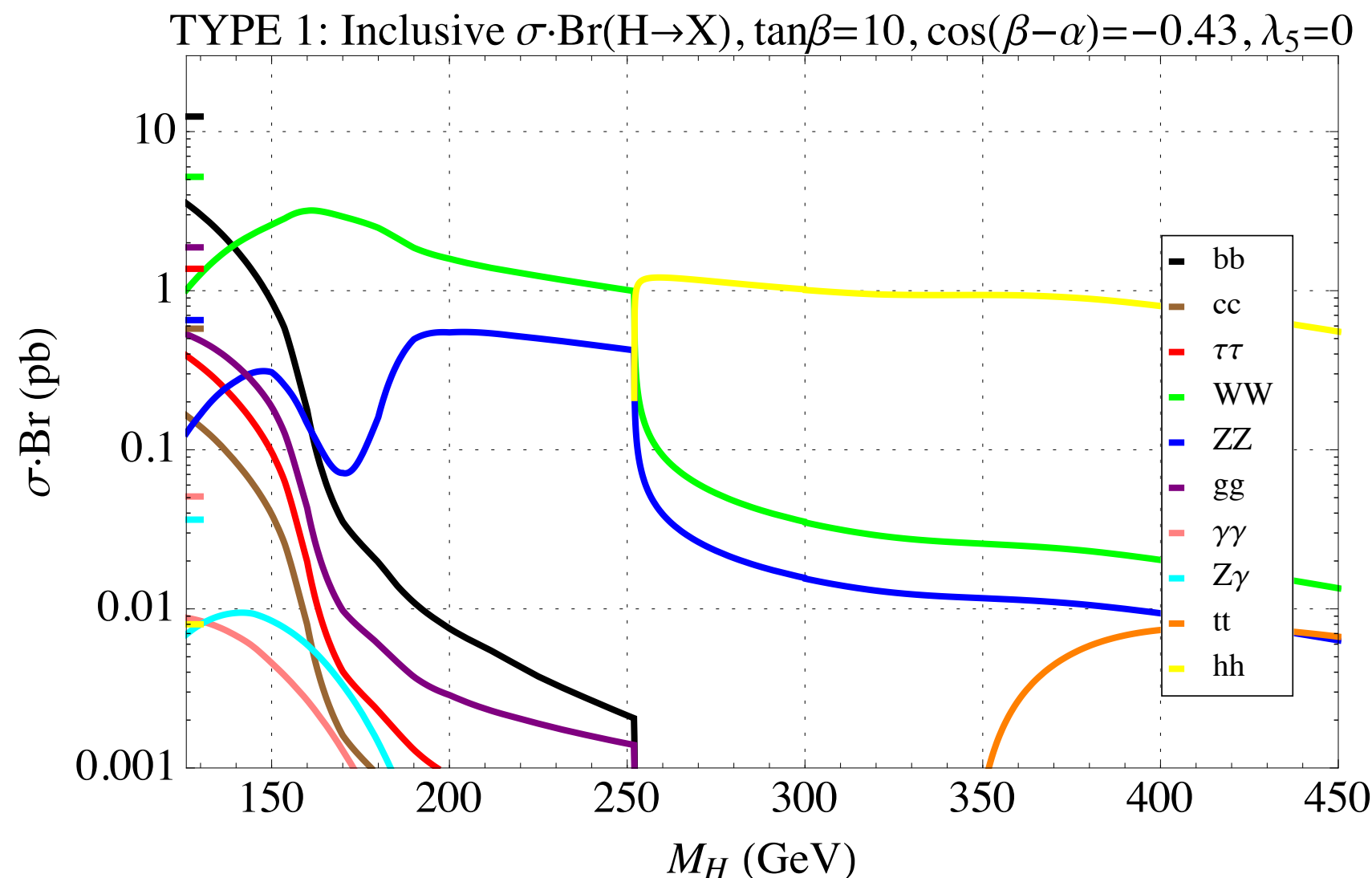- pb-level rates for hh consistent w current fits.

Look for di-Higgs!

TYPE 1: Inclusive $\sigma \cdot \mathrm{Br}(H \rightarrow hh)$ (pb), $m_H = 300$ GeV, $\lambda_5 = 0$

Look for di-Higgs!

TYPE 1: Inclusive $\sigma\cdot\mathrm{Br}(H\rightarrow hh)$ (pb), m_H=300 GeV, λ_5=0

Rule of thumb 3

Top pairs don't always win at high mass.

In Type 1 2HDM, top coupling is suppressed at large tan beta.
So decay of H to hh or A to Zh can dominate at high mass.

TYPE 1: Inclusive $\sigma \cdot Br(H \rightarrow X)$, $\tan\beta = 10$, $\cos(\beta - \alpha) = -0.43$, $\lambda_5 = 0$

Type 1: Combined Fit [68, 95% CL]

Rule of thumb 4

Fermion couplings of H,A are still nonzero in the exact decoupling limit.

So gluon fusion production can still be large, and decays to pairs of taus, muons, photons, bottom quarks can all be appreciable.

bbH, bbA associated production may also play a role.

TYPE 1: Inclusive $\sigma \cdot Br(A \to \gamma\gamma)$ (fb)

TYPE 2: Inclusive $\sigma \cdot Br(A \to \gamma\gamma)$ (fb)
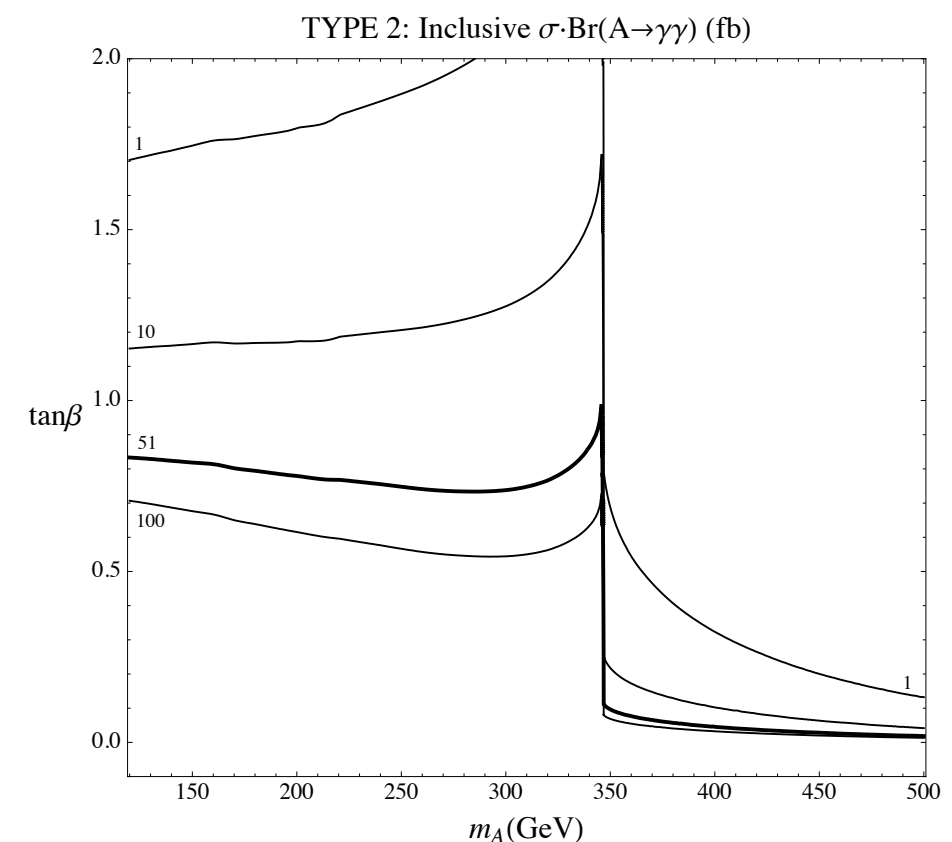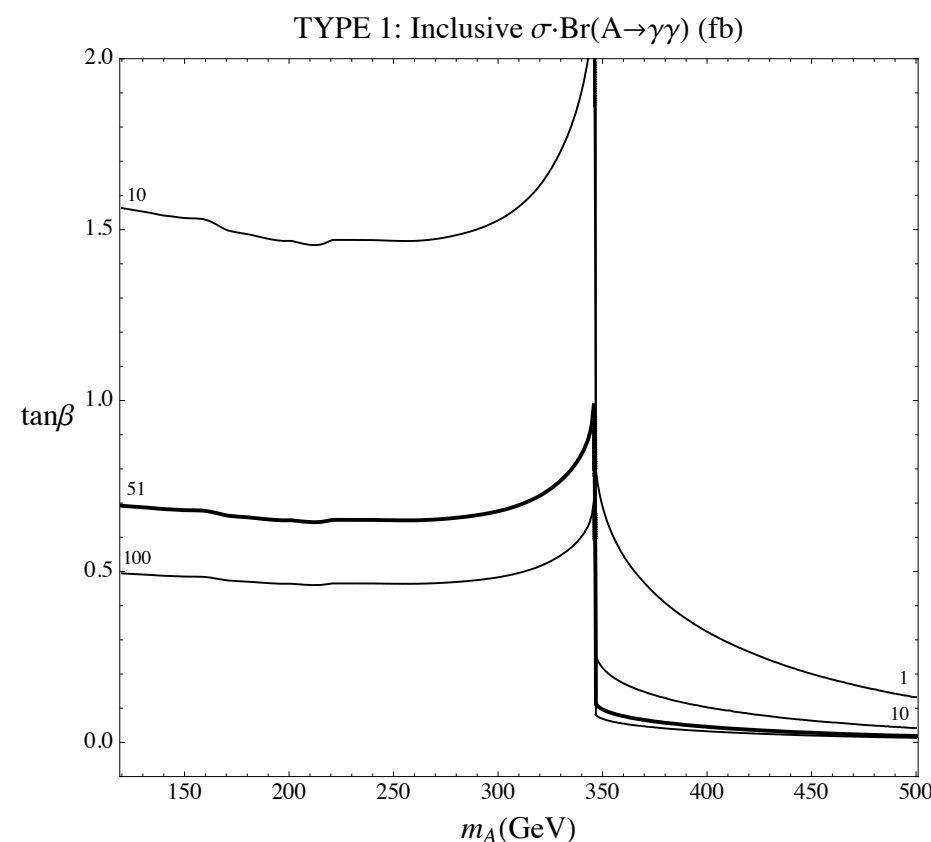
Worth extending these searches to high mass, since they may be the only signal channels if we're unlucky.

What to do?

First priority, look for these processes at proton-proton collider:

- $gg \to A \to Zh$ ← These have not been done yet
- $gg \to H \to hh$ ←

- $gg \to A,H \to$ gamma gamma

- $gg \to A,H \to$ tau tau

- $gg \to H \to VV$

Some of these searches (di-tau) done for MSSM Higgs. But we should search in all channels!

Searches get harder at lepton machines because VA production is zero and VH production is suppressed.

Simulation for Snowmass

Prohibitive to simulate each individual point in the 2HDM parameter space of masses and mixing angles

$$\sigma \cdot \mathrm{Br} \cdot \mathcal{A}(pp \to f) = \sum_t \sigma(pp \to t) \mathcal{A}(pp \to t \to f) \prod_a \mathrm{Br}_a(t \to f)$$

Analytic   Simulation   Analytic

Instead factorize into topologies, compute acceptance for each topology through simulation, then re-weight analytically using functional dependence of cross section and branching ratios.

Simulation for Snowmass

- 2HDM model file in MG4.

- Choose model couplings simply to ensure all topologies are available and widths are sensible.

- Simulate 2-to-2 production of various motivated process in MG4/5.

- Decay h bosons in BRIDGE to exclusive SM final states.

- Use these exclusive topologies to determine acceptance.

- Reweight each topology analytically to determine signal.

14 TeV signal files are ready, more coming.
Many new, interesting studies to be done!

We've discovered one Higgs-like state. Looking for more may be our most promising route to new physics. Substantial new signals are consistent with couplings of the observed Higgs.

Thank you!